Design and Pre-flight Performance of Spider 280 GHz Receivers

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Spider

Spider is a balloon-borne millimeter-wave polarimeter designed to probe for the signature polarization left by primordial gravitational waves (PGW) on the Cosmic Microwave Background (CMB) [1-3]. These divergence-free B-mode patterns are predicted in inflationary models at large angular scales, and the observation of their signature on the sky gives constraints on key cosmological parameters such as the tensor-to-scalar ratio *r*.

In January 2015, Spider mapped ~10% of the southern Galactic sky at 95 and 150 GHz using six monochromatic telescopes during its first flight on a NASA Long Duration Balloon at an altitude of 36 km [4]. Spider's second flight is scheduled for December 2021, with upgrades to the cryogenic system and gondola. Spider will reobserve the same sky area with three new 280 GHz receivers alongside three previously flown receivers: two at 95 GHz and one at 150 GHz.

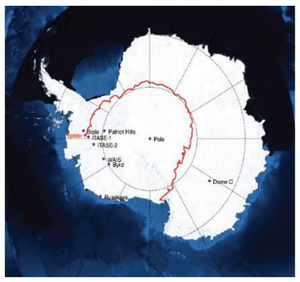

Fig. 1: 16 day flight path launching from McMurdo Station, Antarctica

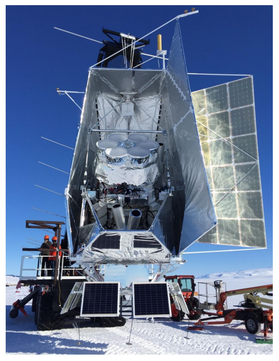

Fig. 2: Fully integrated Spider payload and balloon ready for launch.

Spider 2 Goals

A key challenge for detecting PGW B-mode polarization is isolating the signal from Galactic dust emission, which dominates power spectra at high frequencies. The ability to characterize and remove polarized foregrounds requires deep observations at multiple frequencies. Observing at 280 GHz will provide new information on polarized Galactic dust emission that will help to separate it from the cosmological signal, increasing Spider's sensitivity to place a constraint on r<0.03 with a 3σ confidence level [1,5].

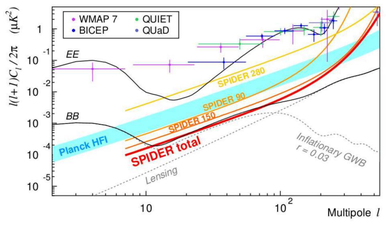

Fig. 3: Spider's expected EE and BB sensitivity as a function of multipole, along with results from some recent experiments [1].

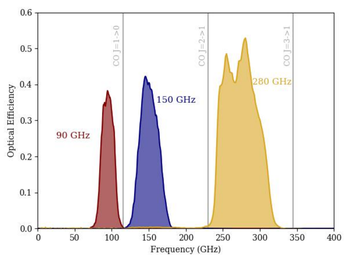

Fig. 4: End-to-end frequency response of the three Spider bands, normalized to reproduce the measured optical efficiencies. Vertical gray lines represent the rotational transition lines of Galactic CO.

280 GHz Receivers

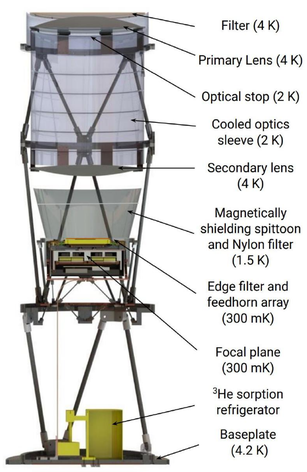

Fig. 5 (Left): Simplified cutaway model of the Spider 280-GHz receivers. The telescopes are ~1.2 meters in length measured from baseplate to the 4 K filter.

(Right): One of the fully constructed 280 GHz receivers. New lenses, carbon fiber trusses, and other hardware alterations were required to accommodate the new optical design. These alterations were performed at the University of Illinois at Urbana-Champaign.

Three previously flown Spider receivers have been reconfigured to accommodate the 280-GHz optical design, which has an effective focal length of 454.7 mm and a field of view of 16.4 degrees across the diagonal. The design optimizes the beam quality and edge taper over the smaller footprint of the 280-GHz focal planes. Receivers include design elements such as baffling between the lenses to suppress internal loading–allowing us to push the detector sensitivity toward the CMB photon noise limit in the low-loading environment at high altitudes.

Focal Planes

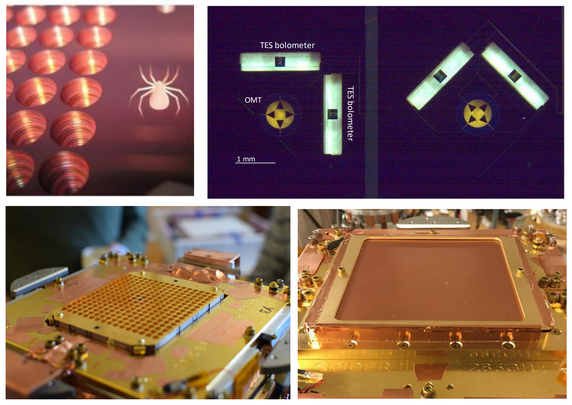

Fig 6: (Top Left): Close up of feedhorn array

(Top Right): Close up showing the alternating orientations of neighboring pixels.

(Bottom Left): Fully assembled focal plane unit with feedhorn array visible.

(Bottom Right): View of focal plane with cutoff filter installed over feedhorn array.

Spider 280 GHz focal plane units (FPUs) utilize feedhorn-coupled arrays of transition edge sensors (TESs) designed and fabricated at NIST. Feedhorns couple to pairs of planar orthomode transducers (OMTs), which direct orthogonal polarization modes to distinct TESs. Neighboring bolometer pairs are rotated by 45° so each array can measure the Stokes Q and U polarization parameters simultaneously. Each bolometer has two TESs connected in series with different superconducting transition temperatures (T_c); an AlMn TES (T_c~420 mK) provides low noise for science data acquisitions, while an Al TES (T_c~1.6 K) extends the bolometer dynamic range for the higher optical loading conditions of lab-based measurements.

Acknowledgements

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Bolometer Parameters

Fabrication of the 280-GHz FPUs achieved high yield with good uniformity across the arrays [7]. Detector parameters were measured at various bath temperatures from 330 – 480 mK, and extrapolated down to the 300 mK flight operating temperature.

FPU	P_{sat}(300 mK) [pW]	T_c [mK]	G_c [pW/K]	R_n [mOhm]	β	Yield
Y3	2.76 ± 4.8%	440 ± 0.8%	27.74 ± 4.6	10.91 ± 2.9	1.88 ± 1.5	86%
Y4b	4.18 ± 4.6%	460 ± 0.9%	36.12 ± 4.3	11.54 ± 2.7	1.76 ± 7.0	86%
Y5	3.54 ± 4.8%	450 ± 0.5%	33.00 ± 4.7	10.68 ± 3.6	2.03 ± 0.9%	95%

Table 1: Device parameters for the 280-GHz arrays. Listed is the median detector saturation power, critical temperature, thermal conductivity at the critical temperature, normal resistance, thermal conductance power law, and detector yield. The variation in measured parameter values is reported at 1 sigma. The names of the 280-GHz FPUs ('Y3', 'Y4b' & 'Y5') are inherited from the Spider-1 FPU from which their packaging came ('X3', 'X4' & 'X5'). 'Y4b' is the second iteration of the Y4 280-GHz array.

Optical Characterization

The 280-GHz receivers have gone under characterization of the internal loading, spectral response (Fig. 4), end-to-end optical efficiency (Fig. 7), and near-field beam mapping (NFBM, Fig. 8). Internal loading characterization is ongoing and will continue with a 4 K cold load mounted in front of the cryostat aperture. The table below summarizes the estimated instrument parameters for Spider's second flight.

Optical Efficiency

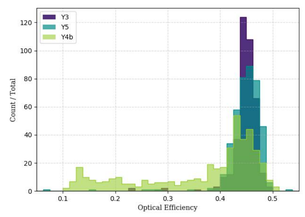

Fig 7. End-to-end optical response of the 280-GHz receivers, accounting for loss from the window, filters, and optics. The tail of low efficiency detectors on Y4b is believed to be a property of the feedhorn array, and they are useful for measuring internal loading in the laboratory loading environment.

Near-Field Beam Map

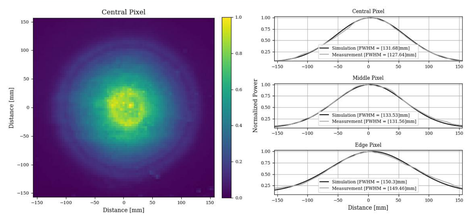

Fig 8. Near-field beam map results for one of the central detectors on the Y4b array, and the cross section of three detectors compared with simulated beams (right). The Y4b NFBM was acquired using a custom stage mounted at the aperture of our test cryostat.

Band	Band Center [GHz]	Band Width [%]	FWHM [arcminutes]	# Spatial Pixels	Total # Detectors	Single Detector Sensitivity [uK·s$^{1/2}$]
95	94.9	26.5	41.3	(2x) 144	572	179.7
150	151.4	25.2	28.8	(1x) 256	512	157.9
280	270.2	26.2	17*	(3x) 256	1536	308*

Table 2: Summary of instrument parameters for Spider's second flight. Listed are telescope band center frequencies and widths, beam width at full-width half-maximum (FWHM), total number of spatial pixels, total number of light sensitive detectors, and per-detector sensitivity. Values listed for the 95 and 150 GHz bands are for only the receivers that will be redeployed in the second flight. (*Denotes estimated values).

References

[1] A. A. Fraisse et al. "SPIDER: probing the early universe with a suborbital polarimeter," *J. Cosmol. Astropart. P.* **2013**,047–047, (Apr 2013).
[2] Filippini, J. P. et al., "SPIDER: a balloon-borne CMB polarimeter for large angular scales," *Proc. SPIE* **7741** (2010).
[3] Ade, P. A. R. et al., "Antenna-coupled TES bolometers used in BICEP2,Keck Array, and SPIDER," *ApJ* **812**, 176 (Oct 2015).
[4] Gualtieri, R. et al., "SPIDER: CMB Polarimetry from the Edge of Space," *J. Low Temp. Phys.* **193**, 1112–1121 (Dec. 2018).
[5] Rahlin, A. S. et al., "Pre-flight integration and characterization of the SPIDER balloon-borne telescope," *Proc. SPIE* **9145** (2014).
[6] Hubmayr, J. et al., "Design of 280 ghz feedhorn-coupled TES arrays for the balloon-borne polarimeter SPIDER," *Proc. SPIE* **9914** (2016).
[7] Bergman, A. S., "Commissioning the SPIDER-2 instrument and SPIDER-1 low level analysis", PhD thesis, Princeton University (2019).